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FREQUENCY STABILIZED GAS LASERS

CONTRACT NO. NAS 8-11773

PHASE I STUDY REPORT
BY
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PREPARED FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA

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ABSTRACT

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"Gain-dither" laser frequency stabilization has been previously demonstrated with 3.39μ lasers at TRG. The changes in parameters necessary to utilize this technique in the visible region at 6328Å are examined through both theoretical and experimental considerations. It is shown that it is necessary to use a 3.39μ laser as an optical pump gain modulator to achieve a satisfactory discriminant for stabilization. With such a pumping scheme, a breadboard stabilization system was constructed. Frequency stability of a few parts in 10^{10} for periods of several minutes was achieved. Conclusions arrived at affecting the design of a stabilized laser package are included.

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I. INTRODUCTION

The objectives of this contract are the design, construction, testing and delivery of frequency stabilized lasers operating at 6328Å. The technique used for obtaining frequency stabilization is inherently the same as has been used by TRG, Inc. to stabilize the frequency of infra-red lasers to one part in 10^{10} [1].

This report describes the work that has been accomplished under Phase I of the present NASA contract. The major emphasis during this phase has been placed on the investigation of modifications necessary to convert TRG's infra-red stable laser system to operation at 6328Å.

The specific goals of this period can be briefly summarized as follows:

1. Determine the optimum parameters of the lasers to be used for stabilization at 6328Å.
2. Fabricate two 6328Å lasers in a bread-board stabilization system for investigation of error signal optimization.
3. Demonstrate the gain-dither stabilization technique at 6328Å.
4. Conduct preliminary investigation of the effect of power and pressure changes on the discriminant.

In the main these goals have been accomplished.

[1] W.R. Bennett, Jr., et al, Appl. Phys. Letters, 5, 56 (1964).

II. GAIN-DITHER TECHNIQUE

A brief description of the stabilization technique will help to clarify the discussion, which follows, of the work accomplished and the difficulties encountered.

The "gain-dither" technique is a null balance method which uses the dispersion of the medium, in the presence of a single-mode oscillation, as the discriminant from which an error signal is derived and used to correct the laser frequency. The dispersion curve is determined by the gain function of the medium and can be calculated from the "Kramers-Kronig" relations. In an inhomogeneous medium (e.g., Doppler broadened), the gain and dispersion in the presence of oscillation are altered as a result of "hole burning"[2]. (See Figure 1.) The presence of a "mirror image hole" in the gain curve produces the dominant effect, a change in the index of refraction at the oscillation frequency. As the resonator is tuned across the fluorescent line a small but significant change in the oscillation frequency relative to the resonator frequency results. This frequency change ("pulling ") is proportional to the depth of the mirror image hole, and hence, upon the strength of the oscillation. Thus, if the gain of the medium is modulated by a small amount ("dithered"), the index of refraction will also be modulated and will produce frequency modulation of the oscillation at the same rate as the dither.

When the oscillation is tuned through line center, the frequency modulation is linearly reduced to a null, and the phase of modulation inverts as the oscillation passes line center.

In the stabilization system, the laser light is detected, the fm demodulated and phase detected, and, in this manner, an error signal is developed with which the cavity is controlled.

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[2] W.R. Bennett, Jr., Phys. Rev. 126, 580 (1962).

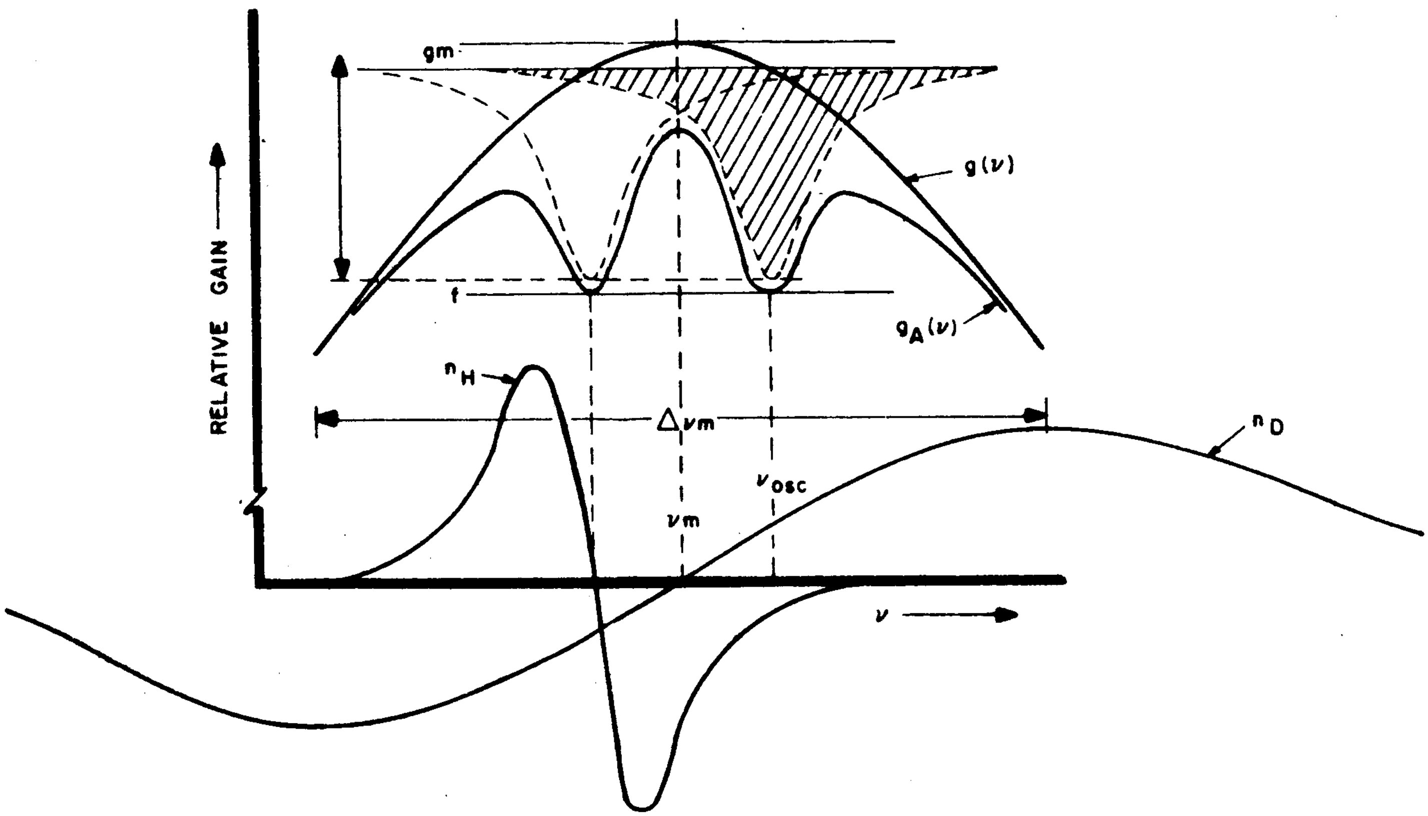

Figure 1. Relative Gain and Index of Refraction of Inhomogeneously Broadened Laser Medium with Oscillation at $\nu = \nu_{osc}$

It should be noted that, in principle, demodulation of the fm could be obtained through the use of an optical discriminator, e.g., a Fabry-Perot interferometer tuned to the side of a resonance. However, a large increase in sensitivity and stability is obtained by translating the optical frequency to radio frequencies with an optical heterodyne receiver and demodulating the error signal using standard rf techniques. It is specifically for this reason that we require a second 6328Å laser for the stabilization system.

III. SINGLE-MODE OSCILLATION AND LASER PARAMETERS

To obtain a usable discriminant it is necessary that the master laser oscillate in only one mode. Should a second oscillation be present, the holes burned in the gain curve by the unwanted oscillation would cause changes in the dispersion of the medium which could make it useless for stabilization. For this reason, considerable effort was placed in constructing a single-mode laser (with as great an output power as possible). The properties of the amplifying medium which produce difficulties in achieving high single-mode power are basically the large Doppler width (1500 Mc), the low gain coefficient, and the dominance of the competing 3.39μ transition.

Mode Suppression

The mode suppression problem can be separated into two parts: (1) elimination of all but one axial mode, (2) elimination of all transverse (angular modes)

The suppression of extraneous axial modes is determined by the gain, Doppler width and cavity length. In general, the length of the cavity must be sufficiently short so that the threshold condition for oscillation is satisfied only over a range that is small compared with the mode spacing ($\Delta\nu = c/2\ell$). This insures that, under all conditions, oscillation can occur in only one axial mode. However, since we are interested in stabilizing near line center, it was possible to relax this condition so that, over a reasonable frequency range around line center, ($\pm$200 Mc), only one axial mode could oscillate. In practice we found it necessary to work with cavity spacing of 30 cm or smaller in order to achieve this range of single axial mode operation.

Suppression of the transverse modes is accomplished by proper choice of cavity configuration and "Fresnel number," commensurate with the threshold gain. In general, the oscillation threshold for transverse modes is somewhat higher than for the axial modes. By choosing the appropriate "Fresnel number," ($N = a^2/\ell\lambda$), where a = tube radius, ℓ = mirror separation, λ = wavelength, the losses for the first transverse mode can be made greater than the net gain of the medium, thus preventing oscillation. An important parameter in choosing the type of cavity to be used is the relative discrimination against transverse modes. By this we mean the fractional amount that threshold can be exceeded on the axial mode before threshold is reached for the first transverse mode. The confocal cavity has the optimum discrimination[3] and, if the limitation that it imposes on mode volume is not a serious consideration, its use is to be preferred. We have used the folded confocal cavity exclusively, and note that, for other configurations (e.g., plane, folded concentric, etc.), the diffraction losses for the axial modes become prohibitive for our resonator dimensions. The Fresnel number of the resonators were made variable through the use of an adjustable iris diaphragm. The aperture was usually adjusted to ~1 mm, providing a Fresnel number of ~1.

Single-Mode Power Outputs

Because the gain coefficient of the 6328Å transition is small, $\sim 10^{-4}$ cm^{-1} for a 1 cm bore plasma tube, it is necessary to use to advantage the inverse relationship between gain coefficient and tube diameter. Thus, by using a plasma tube bore of 1 mm we achieved a single-pass gain of ~2% with a 10 cm long tube. Because of the high electrical impedance of the plasma in such a tube, dc operation with heated filament was the only practical means of excitation. However, this means of excitation subsequently proved detrimental to the stabilization scheme as will

[3] Fox and Li, Proc. IEEE, 51, (1963).

be discussed in Section V, and was, therefore, eventually changed. With dc excitation of the 10 cm plasma in a 15 cm resonator a single-mode output of about 10 μwatts was obtained. (See Figure 2.) We subsequently turned to the use of rf excitation with a larger (3 mm) bore plasma tube and, because of the reduced gain coefficient, employed 30 cm resonators with approximately 20 cm of active plasma, achieving single-mode outputs of 60 μwatts. Although the axial mode separation is not as great as with the shorter dc excited tubes, adequate suppression is achieved.

Isotopic Purity

In addition to other laser properties, the isotopic composition of the medium is important in determining the pulling effects which are used for stabilization.

If more than one isotope is present in significant quantity, a minimum of three holes are burned in the gain distribution rather than two as in the case of a single component. This can result in a discriminant which is dependent on power level, or sufficiently asymmetrical to render it useless for stabilization by the gain-dither technique. For these reasons all the lasers used are filled with high purity Neon 20 (99.98%).

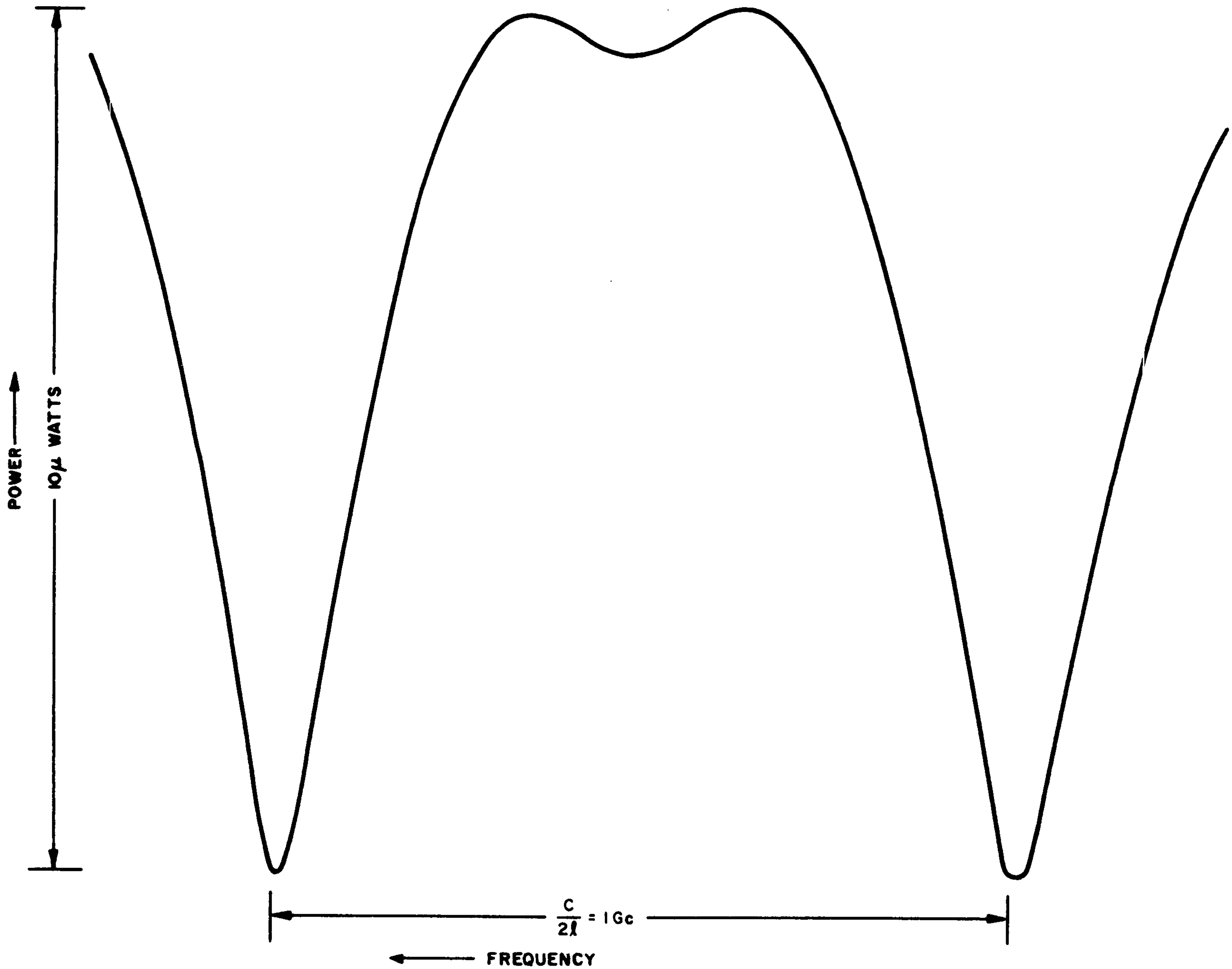

Figure 2. Single Mode Output Power vs Cavity Frequency 6328Å

IV. 3.39μ DOMINANCE AND SUPPRESSION

In addition to the suppression of all but one mode in the stabilized laser, oscillation at 3.39μ must be eliminated. The 3.39μ transition originates from the same upper level as the 6328Å transition, and primarily because of its longer wavelength, has a gain coefficient which is about 100 times greater. Because of the common level, any hole burned in the 3.39μ gain curve as a result of oscillation at that wavelength will likewise produce a hole in the 6328Å gain curve. To this extent, an oscillation at 3.39μ will have a comparable affect on the stabilization discriminant as multi-moding at 6328Å. In addition, because of the enormous difference in gain between the two transitions, small increments in loss at 6328Å can result in the quenching of that transition by the 3.39μ oscillation. For these reasons it is necessary to completely eliminate oscillation at 3.39μ.

We have experimentally investigated several techniques for the suppression of 3.39μ. These include:

A. Selective absorption with organic gases (e.g., methane).
B. Q-spoiling using a dispersive optical element (Brewster's angle prism).
C. Absorption using BK7 glass.

A. We found that both methane and propane were excellent absorbers of 3.39μ radiation. A 2 cm cell flushed with methane at atmospheric pressure produced an attenuation greater than 10^4. Although methane absorption of 3.39μ radiation is adequate in suppressing oscillation, our work has shown that when sealed within the laser resonator slow changes in methane density occur, causing large scale tuning of the oscillator frequency. For this reason it appears that methane absorption is not appropriate in a stabilized laser system since stability of the optical path is of primary importance.

B. Brewster's angle prisms have also been used to extinguish the 3.39μ transition. The arrangement shown in Figure 3b was used, with one plasma tube window replaced by a quartz Brewster's angle prism. This completely eliminated 3.39μ oscillation by effectively misaligning the cavity in the infra-red while maintaining alignment in the visible. This cavity suffers from two serious disadvantages: The broken optical axis makes the construction and alignment of components considerably more difficult than the standard arrangement. The broken axis reduces a critical form of thermal compensation that is present in the standard arrangement. In the entire laser resonator, it is the plasma tube that is subjected to the largest thermal fluctuations, since it is in direct contact with the thermal source. Temperatures of $\sim 100°C$ at the surface of the plasma tube are quite common. In the standard arrangement, see Figure 3a, as the plasma tube expands, it is compensated for by the reduction in the air path. The net change in optical path is $(n_{air} - n_{medium})\Delta L$. Where $n_{air} \cong 1 + 3 \times 10^{-4}$ and $n_{medium} \cong 1$, so that the total change in optical path is $3 \times 10^{-4}\ \Delta L$, or a reduction by a factor of about 3000 in the actual expansion.

With the prism arrangement, this is no longer the case. With a change ΔL in the plasma tube length, the change in optical path as a result of the broken path becomes,

$$(n_{air} \cos\phi - n_{medium})\Delta L \cong (\cos\phi - 1)\Delta L \cong 0.3\ \Delta L\ .$$

So that three orders of magnitude of compensation may be lost. By appropriate construction, however, the plasma tube could be constrained at the prism end, and allowed to expand at the other end. This may improve the condition but coupled with construction and alignment difficulties, it would be preferable to avoid this method in a stabilized system.

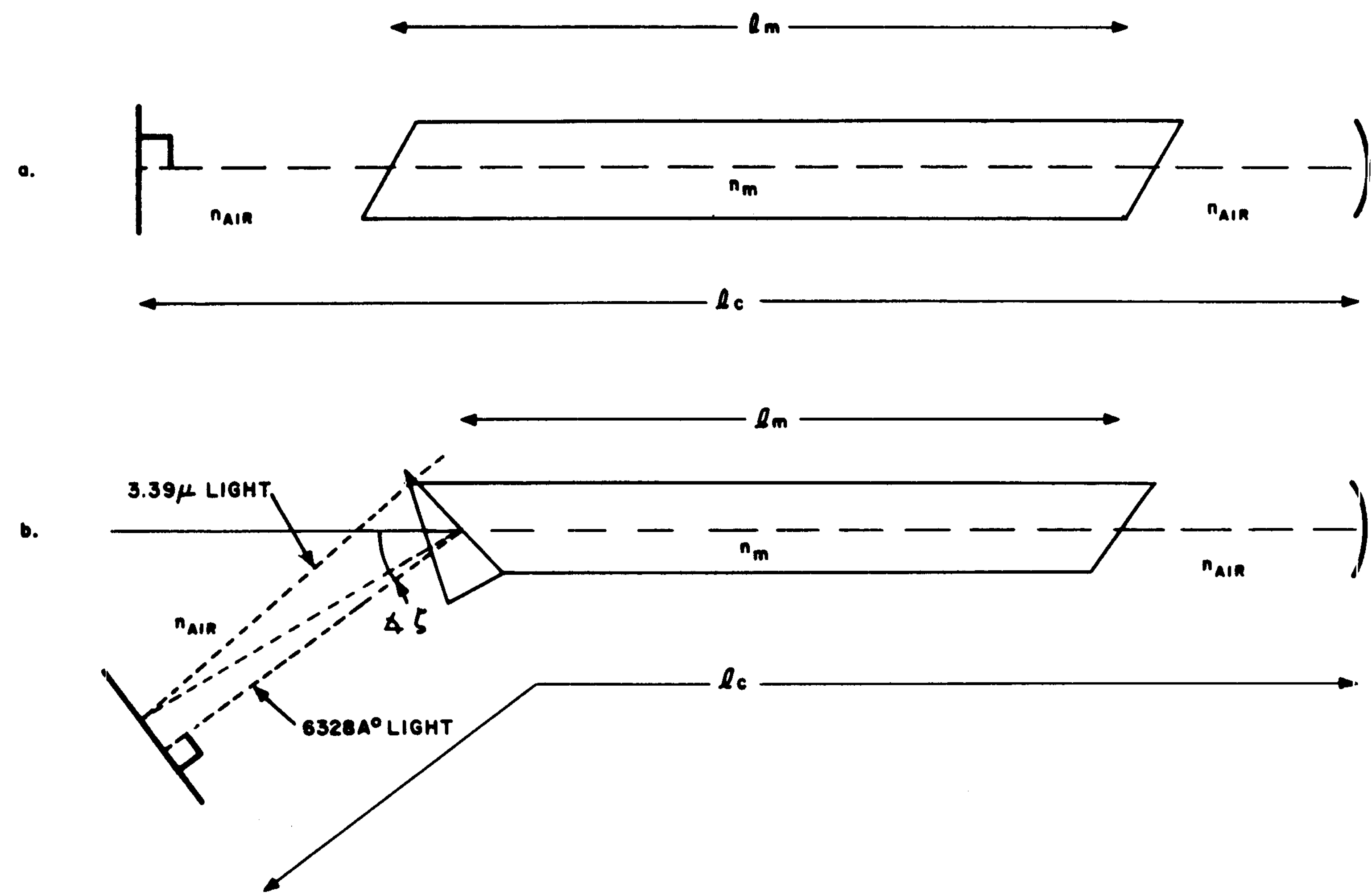

Figure 3. Optical Paths of a) Standard, and b) Brewster's Angle Prism Cavity

C. The use of BK7 glass windows seems, at the present time, to offer the best means of eliminating 3.39μ oscillation in the stabilized laser system. Although the absorption coefficient of thin BK7 glass windows at 3.39μ is relatively small compared with gas absorption, (transmission T ~ 25%, for a 2 mm thick window), it is adequate in preventing oscillation when used with the 3 mm bore rf excited plasma tubes and does not suffer from the drawbacks of the other techniques. We have operated an rf excited 3 mm bore laser with BK7 windows and have obtained outputs of about 60 μwatts in a single mode, free from 3.39μ interference.

It should also be noted that when superior dielectric multi-layer coats are used, (low reflectivity at 3.39μ), it is possible to quench 3.39μ oscillation by appropriately adjusting the iris diaphragm. Oscillation is inhibited at 3.39μ by producing large diffraction losses on the dominant modes. Under these conditions quartz windows may be used on the plasma tube. A somewhat greater power output can be achieved since the scattering and absorption losses of quartz at 6328Å is smaller than that of BK7 glass.

V. ERROR SIGNAL MEASUREMENTS

The major emphasis of this phase of the contract has been placed on obtaining a discriminant by the "gain-dither" technique which can be used for stabilization. Towards this end a bread-board optical heterodyne system was fabricated, and a series of experiments were conducted under varying conditions of excitation, gain modulation and gas pressure to obtain a usable error signal. Figure 4 is a block diagram of the experimental arrangement used for measuring the discriminant. In order to provide variation of gas pressure, the master laser was connected to a gas filling station.

Basically, the system operation is as follows: The AFC loop maintains the beat between the two lasers within the IF bandwidth. Any am modulation on either laser is removed by the limiter and any fm modulation appears at the discriminator output. The fm modulation produced by the gain-dither is compared with the dither driver signal at the phase detector. The output is the error signal. As the master laser is tuned across its fluorescent line, the error signal traces out the discriminant curve.

Dc Excitation

The initial measurements were made with a master laser which employed a 1 mm bore by 10 cm long dc excited plasma tube within a 15 cm optical resonator. When the gain of the master laser was modulated, an anomalous fm error signal was obtained. The signal level was larger than the calculated level by about an order of magnitude and showed no phase reversal or significant variation in amplitude as the master laser was tuned across the fluorescent line. The results were unchanged by variation of gas pressure. The anomaly seemed explainable in terms of phenomena

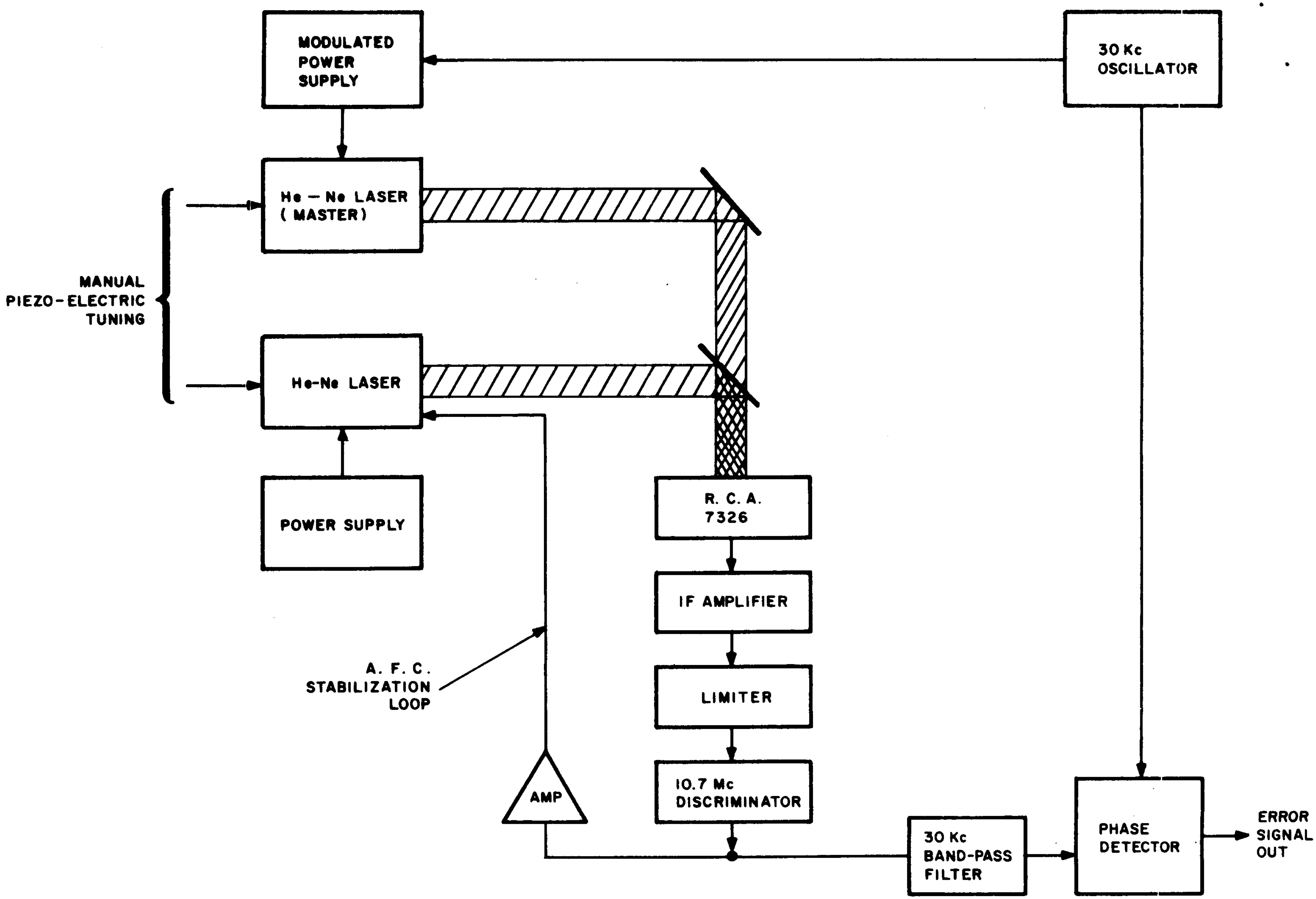

Figure 4. Experimental Arrangement for Error Signal Measurement.

related to plasma oscillations. Namely, a likely possibility was the generation of density variations in the gas (acoustical waves) as a result of ions being driven by the low frequency modulation field. Calculation indicated that variation in the total gas density of 1 part in 10^4 could result in sufficient modulation of the optical path within the resonator to cause the observed anomaly.

We believed that changing from dc excitation to rf would eliminate the difficulty since it was thought that low frequency fields would not be present to directly drive the ions. In addition, we had been successful in the past in obtaining the expected discriminant at 3.39μ with modulated rf excitation.

Rf Excitation

Several plasma tubes were constructed for operation with rf excitation. It was found that plasma tubes with approximately a 3 mm bore could be excited, but difficulties in power matching prevented operating with smaller bores. The lower gain of the 3 mm bore made it necessary to increase the length of the plasma column and as has been previously discussed we operated with a plasma length of ~ 20 cm in 30 cm resonator.

When the error signal measurements were repeated the same anamolous result was observed. At this time we made positive checks to insure that the effects were not in fact spurious. Since pick-up of the modulated rf by the servo electronics or by the transducer in the slave laser could cause the anomaly by directly frequency modulating the laser, we brought in proximity to all the suspect areas a third rf modulated plasma tube in the hope of producing the effect. The results were negative, indicating that the observed signal was geing generated by power modulation of the laser, and not as a result of pick-up.

A question was posed as to why this effect was not observed in the stabilization of the 3.39μ lasers since power modulation of the master laser was also employed. The answer is apparent when the equation for the frequency pulling is examined.

$$\delta\nu_{osc} = \frac{c}{2L\pi H}(\nu_{osc} - \nu_m)\delta g$$

where
c = speed of light
L = cavity spacing
H = hole width
δg = variation in gain
ν_{osc} = oscillation frequency
ν_m = medium center frequency

This equation is valid at 6328Å and to a close approximation is also correct at 3.39μ. The major difference between the two wavelengths is the gain coefficient. For a given percentage of power modulation of the plasma, the modulation of gain at 3.39μ will be approximately 100 times greater than at 6328Å. Therefore, the frequency pulling and error signal will be 100 times greater on the infra-red transition, and the anomaly which is an order of magnitude greater than the expected signal at 6328Å, will only produce a 10% effect at 3.39μ.

We still believe that the anamolous fm is due to the power modulation of the plasma, and related to the geometry used. Although the source of power is at radio frequencies, the rapid diffusion of electrons to the walls of the plasma tube compared with ions tends to produce a negative charge which is proportional to the electron density, hence to the power. Therefore, modulation of the rf power level will produce modulation of the static charge on a sheath near the walls and provide the necessary driving force to produce modulation of the gas density by driving ions through the ballast regions.

We conclude that it is necessary to avoid electrical modulation of the plasma to produce the "gain-dither" at 6328Å.

Optical Pumping Modulation

To avoid the anomolous frequency modulation produced by direct power modulation of the master laser, other techniques of producing gain-dither have been considered. Foremost among these has been optical pumping of the energy levels involved in the laser transitions. By using a radiation source containing the appropriate wavelengths of light, (e.g., a neon plasma tube), the population of the energy levels within the master laser tube may be altered through the absorption or emission of radiation induced by the pumping source. It is then possible by electrically modulating the optical pumping to produce modulation in the master laser without varying in any way its electrical excitation. Three different techniques of optical pumping modulation were considered and investigated:

1. Optical pumping of the lower laser state ($2P_4$) from the metastable 1S levels.
2. Optical pumping of $3S_2 \rightarrow 3P_4$ level with super-radiant 3.39μ radiation.
3. Optical pumping of the $3S_2 \rightarrow 3P_4$ levels with a 3.39μ laser.

In the first technique a neon plasma tube is positioned in close proximity to the master laser plasma tube, and if possible the two are enclosed by a focusing element. Light from the pump is absorbed by metastable 1S neon atoms in the master laser, raising them to the $2P_4$ level and thereby reducing the master laser gain coefficient. The efficiency of the technique depends strongly on the source brightness and on the absorption coefficient (the population density of the neon metastable level).

An experiment was initiated to investigate the technique. An optical pump plasma tube, comparable in dimensions with a laser plasma tube (3 mm bore) was constructed and placed within a few millimeters of the laser tube, without a focusing element. Power modulation of the laser was observed, but the level was so low as to make it useless for obtaining a stabilization error signal. The percentage of modulation undoubtedly could have been increased by increasing the bore of the laser tube and thereby increasing the lifetime and population of this neon 1S metastable. Unfortunately, other considerations which have been indicated, require the use of small bore tubing for the master laser.

The second technique of optical pumping considered, makes use of the high gain 3.39μ transition which has the same upper state, $3S_2$, as the 6328Å transition. The super-radiance (fluorescence) of the 3.39μ transition from a second plasma tube is used to end pump the 6328Å laser. End pumping is possible since the 3.39μ transmission through the 6328Å dielectric reflector is quite large (~80%) and because the transition has gain rather than absorption. In order to achieve a significant level of modulation, the optical field produced by the modulation tube must be comparable with that produced by an oscillator, namely sufficiently strong to saturate the small signal gain at 3.39μ in the master laser.

We constructed a tube 90 cm long with a 3 mm bore which had a single pass output of ~0.3 μwatts at 3.39μ and a double-pased output of 3 μwatts. Unfortunately, the level of modulation produced was found to be inadequate for the stabilization system. An attempt was made to use the super-radiant tube doubled-passed so as to increase the modulation. When this was done, it was found that oscillation could not be prevented at 3.39μ as a result of the large gain, (~10^4 per pass).

The third optical pumping technique which uses a 3.39μ laser is illustrated in Fig. 5. Essentially, the arrangement is the same as was used in the super-radiant pumping experiment. It was found that with a single mode power output of ~ 50 μwatts in the 3.39μ transition a significant percentage of gain modulation could be produced. With about 75% modulation of the 3.39μ output, a peak to peak gain change of 6×10^{-4} was measured in the 6328Å laser; this is an adequate gain variation to generate an error signal with sufficient signal to noise ratio to detect frequency errors of 1 part in 10^{11}, the goal of the system.

It should be noted that the change in gain produced by the 3.39μ laser in the 6328Å gain curve is not uniform because the 3.39μ oscillator "burns a hole" in the gain curve at a frequency determined by the 3.39μ oscillation frequency which is not necessarily at line center. However, the pulling effect on the 6328Å oscillation frequency is determined by the round trip integrated gain through the 6328Å resonator; thus, a "hole burned" in one side of the Doppler broadened gain distribution with respect to the wave traveling in one direction in the resonator appears at a frequency symmetrically opposite line center with respect to the wave traveling in the opposite direction. The net effect of the "hole burning," therefore, is to produce a non-uniform variation in gain coefficient which to first order is symmetrical with respect to line center and, hence, usable for stabilization. In addition because the Doppler broadening is proportion to frequency, a hole of width Δf burned in the 3.39μ gain distribution is broadened to approximately $5.4\Delta f$ in the 6328Å gain curve. Since $\Delta f = 230$ Mc[1], the hole burned in the 6328Å gain curve is greater than 1 kMc. This results in an almost uniform as well as symmetric variation in gain when optically pumping with a 3.39μ laser.

[1] Ibid.

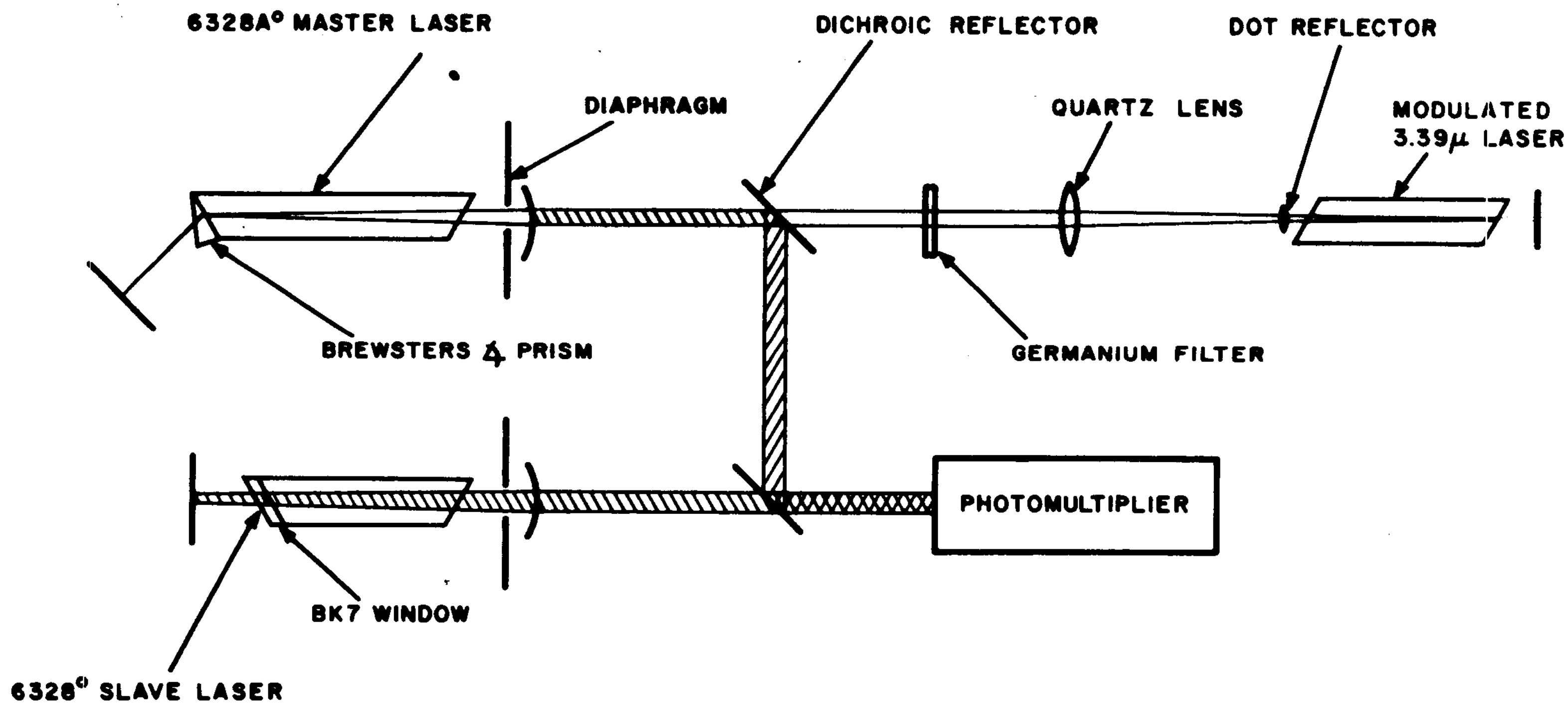

Figure 5. Arrangement for "Gain-Dither" by 3.39μ Optical Pumping

VI. BREADBOARD STABILIZATION

A breadboard stabilization system consisting of the three lasers used to measure the discriminant was constructed by simply closing the electronic loop by feeding back the error signal from the phase detector output to a stacked piezo transducer within the master laser. A Type "0" loop with a gain at dc of $\sim$46 db and cross-over at 100 cps was initially employed to demonstrate the feasibility of the stabilization technique. Since only one system was used, it was not possible to measure the degree of absolute stability accomplished, however, in terms of the error signals measured, the stability was indicated to be a few parts in 10^{10} for periods of several minutes. This by no means represents the system limitation.

3.39μ Pulling Effects

In addition to demonstrating the feasibility of the technique we were able to determine the effect on the null point tuning the 3.39μ laser produced. Namely, by modulating the frequency of the 3.39μ laser at a rate greater than the cross-over frequency of the stabilization loop, the derivative of the frequency pulling as a function of 3.39μ frequency was detected by measuring the amount of modulation produced at the output of the phase detector while the loop was closed. It was determined in this manner that the rate of change of pulling was maximum when the 3.39μ laser is tuned to line center giving a 1 Mc change in the null point for a 10 Mc change in the 3.39μ frequency. However, with the 3.39μ laser tuned to either side of its fluorescence line, this was reduced to 1 part in 3000. This indicates that the 3.39μ laser "burns a hole" in the 6328Å gain curve which is not symmetrical about line center and which probably is a result of collision induced asymmetries in the fluorescence line. This result also indicates the need for a crude stabilization of the 3.39μ laser, most profitably at the point on the side of the line which represents a stationary point in the pulling.

Bi-Laser Cavity

As a possible alternative to the three laser stabilization system, consideration was given to a technique that would combine the 3.39μ modulation laser with the 6328Å master laser in a bi-laser prism cavity, with a common plasma tube.

This technique would in principle be superior to having a separate 3.39μ laser because, by sharing a common cavity, the 3.39μ laser would be simultaneously stabilized, and hence any pulling effects as a function of 3.39μ drift would be minimized. We found that it was possible to control both oscillation levels in the common cavity, and obtain single mode operation on both transitions. In addition, the 6328Å laser could be amplitude modulated by frequency modulating 3.39μ oscillation.

The major concern with the technique was the possibility of mechanical coupling between the 6328Å cavity and the transducer producing the frequency modulation of the infra-red oscillation. Measurements were made of the effect in a simulated test by applying voltage to a single PZT-5 element which was mechanically contacted to the prism laser. Although the mechanical amplitude involved in the test was only 1% of what would be required to produce adequate gain modulation, a large percentage of frequency modulation of the red oscillation was observed, indicating strong mechanical coupling. The level of spurious modulation was sufficient to make this technique unfeasible for use in laser stabilization.

VII. CONCLUSIONS

The basic goal of the study phase of the program has been the determination of changes necessary to alter TRG's stable laser system at 3.39μ for use at 6328Å.

Most of the conclusions have already been given in the various sections of the report. However, reiterating the major points for design consideration:

1. It is necessary for frequency stabilization by "gain-dither" at 6328Å to employ a third, crudely stabilized, 3.39μ laser as an optical pump modulator to produce the discriminant.
2. The laser resonators should be 30 cm long, to prevent multiple axial mode oscillation and obtain optimum power output.
3. An iris diaphragm should be used to quench transverse modes.
4. 3.39μ oscillation can be most effectively suppressed with BK glass windows, and high quality dielectric reflectors.
5. Rf excitation should be employed to produce stable, noise free operation.
6. Isotopically pure neon should be used [Neon 20$\approx$99.98%].